POLARISATION OF LIGHT*

II.

THE experiment described in the previous article, in which the rays reflected from the pile of glass plates are extinguished by the analyser when in one position, while those which have been transmitted are extinguished when the analyser is in a position at right angles to the former, shows that the vibrations of the reflected and refracted rays, so far as they become polarised, are at right angles to one another. And further, if these rays be severally examined with a plate of tourmalin, it will be found that the vibrations of the reflected ray are executed in a direction perpendicular to the plane of incidence, and those of the refracted ray in a direction parallel to that plane.

The same general reasoning as that used in the case of tourmalin plates will serve, if not as actual proof, at all events as illustration in this case. Thus, suppose that a ray whose vibrations are perpendicular to the plane of incidence, that is, parallel to the reflecting surface, fall upon a plate of glass; then there is no apparent reason why a change in the angle of incidence should modify the reflection and refraction, so far as they depend directly upon the direction of the vibrations. The vibrations cannot undergo any change of direction on one side rather than on the other by incidence on a surface to which they are parallel, and will consequently remain parallel to themselves even when the incidence has taken place. And since the reflected and refracted rays both lie in the plane of incidence, the vibrations (which are perpendicular to that plane and consequently to every line in it) will fulfil the optical condition of being perpendicular to the rays in question. But if the vibrations of the incident ray take place in the plane of incidence, it is difficult to conceive that the results of reflection and refraction should be unaffected by a change in the angle of incidence. There are two mathematical and mechanical principles which, when applied to the case of vibrations in the plane of incidence, lead to the conclusion that if the ray be incident at such an angle that the reflected and refracted rays are perpendicular to one another, there can be no reflected ray.

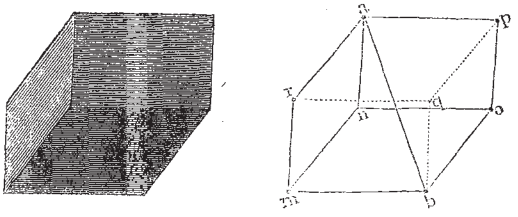

FIG. 9.

A general explanation of this very curious result seems difficult; but the following considerations may perhaps tend to elucidate the subject. Reflexion is generally, perhaps always, accompanied by refraction. Bodies are visible in virtue of rays which, after reflexion from their surface, meet the eye. But the natural colours of bodies so seen are due to rays which are not reflected until they have penetrated to some, although inconsiderable, depth below the actual surface. During this penetration the light has been deprived of certain of its component rays, and emerges as a reflected beam covered with the remaining or complementary tint. And although the colourless reflexion from polished surfaces is an apparent exception to the rule, it may still be the fact that this is only a limiting case in which the penetration is a minimum. If this be so, we may fairly conclude that refraction is the ruling feature of the phenomenon, and that it in some sense precedes reflexion. With the change of direction of the ray involved in refraction it is in the highest degree probable that a change of direction of the vibrations (supposed always to be in the plane of incidence) will be also involved. The simplest supposition would be that the vibrations within the medium are perpendicular to the refracted ray; and that the intensity of the reflected light is due to that part of them which can be resolved in a direction perpendicular to that of the reflected ray. If, therefore, the refracted and the reflected rays be perpendicular, so also will be their vibrations, and consequently no part of the vibrations constituting the former can be resolved in the direction requisite for the latter. In other words there will be no reflected ray.

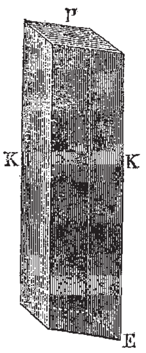

FIG. 10.

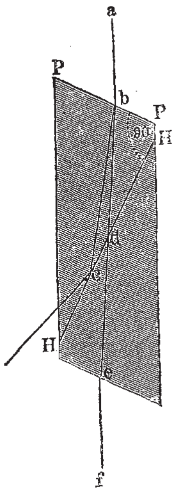

FIG. 11.

The above remarks give, it must be admitted, no mechanical theory of reflexions, nor indeed do they pretend to be even a rough explanation of the facts. They merely amount to this: If reflexion depends primarily upon refraction, and the known law of reflexion obtains independently of all questions of polarisation, then when the incident vibrations take place in the plane of incidence no reflected ray, whose direction is perpendicular to that of the refracted ray, can be produced.

We next come to the subject of polarisation by double refraction. There are a large number of crystals which have the property of generally dividing every ray which passes through them into two. But the extent of separation of the two rays varies with the direction of the incident ray in reference to the natural figure of the crystal. In every double refracting crystal there is at least one, and in many there are two, directions in which no such separation takes place. These directions are called optic axes. The relations between the forms of crystals and their optic axes, and optical properties arising therefrom, will be explained later.

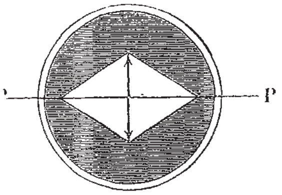

FIG. 12.

Of such crystals Iceland spar is the most notable instance. If we take a block of such spar split into its natural shape, a rhombohedron, Fig. 9, and for convenience cut off the blunt angles by planes perpendicular to the line joining them, a b, it will be seen that a ray of light, transmitted perpendicularly to these planes, that is parallel to the line joining the blunt angles, is not divided. In fact, the image either of the aperture of the lantern projected on a screen, or of an object seen by the eye in the direction in question, appears single, as if passed through a block of glass. The direction in question (viz., the line a b itself, and all lines passing through any part of the crystal parallel to a b), is called the optic axis of the crystal. If, however, the crystal be tilted out of this position in any direction, it will be seen by the appearance of two images instead of one, that the rays are divided into two. The angular divergence of the two sets of rays, or what comes to the same thing, the separation of the two images, depends upon the angle through which the crystal has been turned; or, as it may also be expressed, upon the angle between the directions of the incident ray and the optic axis of the crystal. When this angle amounts to a right angle, the separation is at its greatest; and if the crystal be still further turned, the images begin to come together again until, when it has turned through another right angle, they coincide.

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* Continued from p. 129.

This process of separation, or doubling the rays, is called double refraction. And the following experiment will show that one set of rays follows the ordinary law of refraction, while the other follows a different law. The image produced by the first set of rays is, in consequence, called the ordinary, and that produced by the second the extraordinary image. Let us now take a sphere of Iceland spar, which will act upon the rays issuing from the lamp as a powerful lens. In every position in which it is placed it produces two images on the screen; but in that in which I now place it the two images are concentric, differing only in this, that one is larger than the other. The direction in which the light is now passing is that of the optic axis; and it is to be observed that, although there is a difference in the magnifying of the two images, there is still no divergence of rays, or separation of images in the sense used before. In fact, if we suppose the curvature of the lens to be gradually diminished, we should find the difference of the sizes of the two images, as well as the absolute size of both, diminish; until when the surfaces of the lens became flat, the difference would vanish, and the two images would absolutely coincide.

This difference in the size of the images shows, moreover, a very important property of double refracting crystals. The amount of refraction produced by a transparent medium standing in air depends, as is well known, upon the velocity with which a ray of light traverses the medium compared with that with which it traverses air. The smaller the velocity in the medium, the greater the refraction. The greater the refraction, the greater the magnifying power of a lens constructed of that medium. Hence in the two concentric images we can at once point to the system of rays which has traversed the crystal at a lower velocity than the other.

Let us now turn the crystal round into some other position, so that the direction of the optic axis shall no longer coincide with that of the rays from the lamp or from the object. During this process one of the images, the larger, remains stationary, as would be the case with the single image, if we had used a sphere of glass. This, therefore, is the ordinary image. The other shifts about, separating itself from the first, until the crystal has been turned through half a right angle, and then drawing back again until the crystal has swept round through a complete right angle. This is, consequently, the extraordinary image.

It will be noticed that when the sphere has been turned through a right angle, the extraordinary image is no longer circular, but elliptical, and that the major axis of the ellipse lies in the direction in which the motion has taken place, that is, perpendicular to the axis about which the sphere has been turned. This is due to the fact, shown above, that the nearer the direction of the incident rays to that of the optic axis, the less the divergence between the ordinary and the extraordinary rays. The distortion of the image when the sphere has turned through half a right angle is due to the difference of angles between the optic axis and the rays which enter the crystal on one side and on the other of the central ray of the beam coming from the lamp.

That the rays forming each of the images are polarised, and that the direction of their polarisation is different, is easily shown by interposing a plate of tourmalin or other polarising instrument between the lamp and the sphere of spar. But inasmuch as the polarisation in many positions of the sphere is far from uniform, the phenomenon becomes rather complicated; and the character of the polarisation of the two images is better studied by using flat instead of curved surfaces for separating the rays.

For the purpose in question there is, perhaps, no better instrument than the double-image prism. This consists of a combination of two prisms, one of Iceland spar, so cut that the optic axis is parallel to the refracting edge; the other of glass, and usually having a refracting angle equal to that of the spar. The rays passing through the crystal prism being perpendicular to the optic axis, undergo the greatest separation possible. And the chromatic dispersion caused by that prism is corrected or neutralised entirely in the case of the extraordinary, and nearly so in that of the ordinary ray, by the glass prism which is placed in a reversed position. In this arrangement the extraordinary image occupies the centre of the field, and remains fixed while the double-image prism is made to revolve in a plane perpendicular to the incident rays; while the ordinary image is diverted to a distance from the centre, and revolves in a circle about that centre, when the prism revolves.

If the nature of the light in the two images thus formed be examined by any polarising instrument, it will be found to be polarised in both cases; but that the vibrations in the one image are always perpendicular to those in the other. And in particular the vibrations in the extraordinary image are parallel, and those in the ordinary are perpendicular to the optic axis.

On these principles polarising and analysing instruments have been constructed by various combinations of wedges or prisms of Iceland spar, the details of which it is not necessary to describe in full. But the general problem, and object proposed, in all of them has been to cause such a separation of ordinary and extraordinary rays, that one set of rays may, by reflexion or other methods, be further diverted and afterwards thrown altogether out of the field of view. This done, we have a single beam of completely polarised light and a single image produced from it.

One such instrument, however, the Nicol's prism, on account of its great utility and its very extensive use, deserves description. A rhombohedron of Iceland spar double of its natural length is taken (see Fig. 10); and one of its terminal faces P, which naturally makes an angle of 71° with the blunt edges K, is cut off obliquely so as to give the new face, say P′ (not given in the figure), an inclination of 68° to the edges K. The whole block is then divided into two by a cut through the angle E in a direction at right angles to the new face P′; the faces of this cut are then carefully polished, and cemented together again in their original position with Canada balsam. Fig. 11 represents a section of such a prism made by a plane passing through the edges K (Fig. 10). A ray entering as a b is divided into two, viz., b c the ordinary, and b d the extraordinary. But the refractive index of the Canada balsam is 1·54, *i.e.* intermediate between that of the spar for the ordinary (1·65) and the extraordinary (1·48) rays respectively; and in virtue of this the ordinary ray undergoes total reflexion at the surface of the balsam, while the extraordinary passes through and emerges ultimately parallel to the incident ray. Fig. 12 shows an end view of a Nicol's prism, the shorter diagonal in the direction of vibration of the emergent polarised ray.

Two such instruments, when used together, are respectively called the "polariser" and the "analyser," on account of the purposes to which they are put. These, when placed in the path of a beam of light, give rise to the following phenomena, which are, in fact, merely a reproduction in a simplified form of what has gone before.

When polariser and analyser are placed in front of one another, with their shorter diagonals parallel, that is, when the vibrations in the image transmitted by the one are parallel to those in the image transmitted by the other, the light will be projected on the screen exactly as if only one instrument existed. If, however, one instrument, say the analyser, be turned round, the light will be seen to fade in the same way as in the case of the tourmalin plates; until, when it has been turned through a right angle, or as it is usually expressed, when the polariser and analyser are crossed, the light is totally extinguished.

In the complete apparatus or polariscope, we may incorporate any system of lenses, so that we may make use of either parallel or convergent light, and finally focus the image produced upon the screen or upon the retina. At present we shall speak only of the phenomena of colour produced by crystal plates in a parallel beam of polarised light—chromatic polarisation, as it is called, with parallel light.

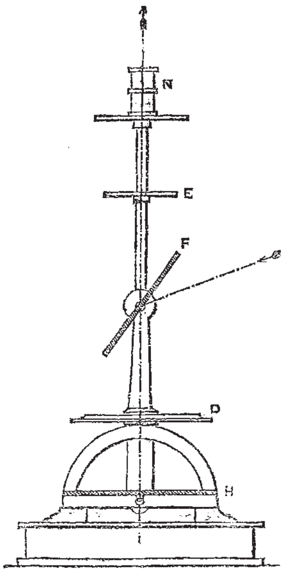

FIG. 13.

Various forms of polariscopes have been devised, whereof the three described below may be regarded as the most important.

Fig. 13 is an elevation of one of them. When used in its simplest form, the frame F carries a plate of black glass which is capable of revolving about pivots in the uprights. The positions of the source of light and of the frame must be adjusted so that the plate will receive the incident light at the polarising angle, and reflect it in the direction of the eye-piece which contains a Nicol or other analyser. The objects to be examined are to be placed on the diaphragm E.

This instrument may be converted into another form, due to Norremberg, by placing a silvered mirror horizontally at H. The plate of black glass must be removed from the frame F, and a plate of transparent glass substituted for it, which must be so inclined that the light falling upon it shall be reflected at the polarising angle perpendicularly towards the horizontal mirror. The object may be placed on the diaphragm E as before. But it may also be placed on the diaphragm D below the polarising plate F, and in that case the eye will receive the polarised ray reflected from the mirror; and the polarised ray will have passed, before it reaches the eye, twice through the crystalline plate placed between the mirror and the polariser. The result is the same as if, in the ordinary apparatus, the polarised ray had passed through a plate of double the thickness. If the plate does not fill the entire field of view two images of the plate will be seen, the one larger, as viewed directly, the other smaller, as viewed after reflection from the horizontal mirror; the first will show the tint due to the actual thickness of the crystal, the other that due to a plate of the same crystal, but of double the thickness.

A further modification of this instrument will be described hereafter.

W. SPOTTISWOODE

(*To be continued.*)

GALILEO'S WORK IN ACOUSTICS

IN looking through the "Dialoghi delle Nuove Scienze" of Galileo, I came unexpectedly on a passage[*] containing two remarkable discoveries in acoustics, which I should have confidently referrred to a much later age. For the sake of such of your readers as may share the same erroneous impression, I hope you will allow me to give, in NATURE, a short account of these results.

The first is a perfectly accurate explanation of the phenomenon called "resonance." Every pendulum has a fixed period of oscillation peculiar to itself. Even when the "bob" is of considerable weight it is possible to set it swinging through a large arc by merely blowing against it with the mouth, provided the successive puffs are properly timed with reference to the pendulum's period of vibration. In the same way a single ringer can, by regular pulling, throw the heaviest bell into oscillations of such extent as to be capable of lifting half-a-dozen men who should hang on to its rope, off the ground all together. When a string of a musical instrument is struck, its vibrations set the air in its vicinity trembling, and the tremors thus set up spread themselves out through space. If they fall on a second wire in unison with the first, and therefore prepared to execute its vibrations in the same period, the effects of the successive impulses are accumulated, and the wire's oscillations can be distinctly seen to go on dilating until they have attained an extent equal to those of the wire originally struck.

Anyone who looks into the chapter on resonance in the "Tonempfindungen" will see that the account of the phenomenon given by the greatest living acoustician is, in principle, identical with that of Galileo.

The second point to which I wish to draw attention is an experiment involving the earliest direct determination of a vibration-ratio for a known musical interval. Galileo relates that he was one day engaged in scraping a brass plate with an iron chisel, in order to remove some spots from it, and noticed that the passage of the chisel across the plate was sometimes accompanied by a shrill whistling sound. On looking closely at the plate, he found that the chisel had left on its surface a long row of indentations parallel to each other and separated by exactly equal intervals. This occurred only when the sound was heard: if the chisel traversed the surface silently, not a trace of the markings remained. It was found that a rapid passage of the chisel gave rise to a more acute, a slower to a less acute, sound, and that, in the former case, the resulting indentations were closer together than they were in the latter. After repeated trials two sets of markings were obtained which corresponded to a pair of notes making

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[*] Opere complete di Galileo Galilei. Vol. xiii. pp. 97-110. (Firenze.)